DTU Library

Window and door opening behavior, carbon dioxide concentration, temperature, and energy use during the heating season in classrooms with different ventilation retrofits—ASHRAE RP1624

Heebøll, Anna; Wargocki, Pawel; Toftum, Jørn

Published in:
Science and Technology for the Built Environment

Link to article, DOI:
10.1080/23744731.2018.1432938

Publication date:
2018

Document Version
Publisher's PDF, also known as Version of record

Science and Technology for the Built Environment

ISSN: 2374-4731 (Print) 2374-474X (Online) Journal homepage: http://www.tandfonline.com/loi/uhvc21

Window and door opening behavior, carbon dioxide concentration, temperature, and energy use during the heating season in classrooms with different ventilation retrofits—ASHRAE RP1624

Anna Heebøll, Pawel Wargocki & Jørn Toftum

To cite this article: Anna Heebøll, Pawel Wargocki & Jørn Toftum (2018) Window and door opening behavior, carbon dioxide concentration, temperature, and energy use during the heating season in classrooms with different ventilation retrofits—ASHRAE RP1624, Science and Technology for the Built Environment, 24:6, 626-637, DOI: 10.1080/23744731.2018.1432938

To link to this article: https://doi.org/10.1080/23744731.2018.1432938

Science and Technology for the Built Environment (2018) **24**, 626–637
Published with license by Taylor & Francis
ISSN: 2374-4731 print / 2374-474X online
DOI: 10.1080/23744731.2018.1432938

Window and door opening behavior, carbon dioxide concentration, temperature, and energy use during the heating season in classrooms with different ventilation retrofits—ASHRAE RP1624

ANNA HEEBØLL[1], PAWEL WARGOCKI[2], and JØRN TOFTUM[3,*]

[1]*Danish Technological Institute, Tåstrup, Denmark*
[2]*Section of Indoor Environment and Building Physics, Department of Civil Engineering, Technical University of Denmark, Lyngby, Denmark*
[3]*Department of Civil Engineering, Technical University of Denmark, Nils Koppels Allé, Building 402, DK-2800 Lyngby, Denmark*

The aim of the present study was to extend the knowledge on the suitability and performance of different ventilation retrofit solutions for school buildings located in a temperate climate. A unique approach was used, where four similar and adjacent classrooms in the same school unit located north of Copenhagen, Denmark, were retrofitted either with a decentralized, balanced supply and exhaust mechanical ventilation unit with heat recovery; automatically operable windows with an exhaust fan; automatically operable windows with alternating counter-flow heat recovery through slots in the outside wall; or a visual feedback display unit showing the current classroom carbon dioxide concentration, thus advising when the windows should be opened. For comparison, one classroom retained the original approach for achieving ventilation by manual opening of windows. One year after retrofitting the classrooms carbon dioxide concentrations, temperatures, energy use, and window and door opening behavior were recorded during a four week period in the heating season in January. The measured carbon dioxide concentrations were significantly lower in the classrooms with the mechanical ventilation system and the system with automatic window opening and an exhaust fan as compared with the classrooms with automatic window opening and heat recovery, with visual carbon dioxide feedback and where windows were opened manually. The automatically controlled windows were open for 71% of the occupied time including breaks with an exhaust fan and for 49% with heat recovery. The façade windows were open up to 17% of the occupied time including breaks in the classrooms with manual window opening (with or without visual feedback). The classroom temperature was generally within the recommended thermal comfort range. The present results indicate that in temperate climates the mechanical ventilation system and both systems with automatic window opening are the recommended systems for classrooms in temperate climates. Providing simply visual feedback on the current carbon dioxide concentration, as a motivation for window opening, did not do so.

Received December 13, 2016; accepted January 3, 2018
Anna Heebøll, MSc, is a Consultant. **Pawel Wargocki, PhD,** Associate Member ASHRAE, is an Associate Professor. **Jørn Toftum, PhD,** is an Associate Professor.
*Corresponding author e-mail: jt@byg.dtu.dk
Color versions of one or more of the figures in the article can be found online at www.tandfonline.com/uhvc.

Introduction

Numerous studies have shown that inadequate ventilation in classrooms in elementary schools reduces the comfort, performance, and attendance of the pupils and increases the prevalence of negative health symptoms (e.g., Bakó-Biró et al. 2012; Daisey et al. 2003; Gaihre et al. 2014; Haverinen-Shaughnessy et al. 2011; Mendell et al. 2014; Wargocki et al. 2002, Wargocki and Wyon 2013). Recent cross-sectional studies in classrooms in schools in Denmark and abroad have documented that classroom air quality is often characterized by carbon dioxide (CO_2) concentrations considerably higher than the maximum of 1000 ppm, which is typically recommended by current guidelines and building codes (e.g., Energistyrelsen 2014; ISO 15251-2007). This has been reported to occur particularly often in classrooms where ventilation is achieved by manual window opening, especially during the heating season in temperate regions (Clausen et al. 2014; Gao et al. 2014; Hellwig et al. 2009; Rosbach et al. 2016; Santamouris et al. 2008; Shendell et al. 2004; Stabile et al. 2016; Toftum et al. 2015).

Improving ventilation in elementary school buildings can be achieved by retrofitting existing classrooms or by the construction of new school buildings, the former being easier to implement, but both being generally considered as costly investments. An interim alternative solution to either could be to motivate students and teachers to change their behavior, by encouraging them to manually open the windows and in this way increase the ventilation rate. The performance of different methods of controlling ventilation in a naturally ventilated classroom was evaluated by Griffiths and Efthekari (2007) who found that it was difficult to meet air quality requirements in a heating season scenario without compromising thermal comfort.

The efficacy of improving the ventilation rate by manually opening windows is greatly affected by the outdoor conditions, including the location of the school (urban and/or rural), by climatic conditions (wind speed and direction, outdoor temperatures), and by how customary it is for pupils and teachers to open windows. It also depends on the classroom layout and on whether single-sided or cross-ventilation can be established. Based on measurements of air tightness in classrooms in an Italian school, Stabile et al. (2016) found that even in poorly maintained classrooms, the permeability of the envelope was too low to guarantee acceptable air exchange rates. The study also showed that during the fall and winter seasons airing seemed ineffective. Wyon et al. (2010) demonstrated in a field intervention experiment that although pupils and teachers readily opened windows when the classroom became warm, they seldom did so when the air quality was poor, possibly because they did not perceive the poor air quality due to gradual sensory fatigue (also known as adaptation, Gunnarsen and Fanger 1992). High temperature seems to be a more important factor driving window opening than any other (Dutton and Shao 2010; Fabi et al. 2013), and during cold weather window opening may seldom occur because of thermal discomfort due to the admission of cold outside air and draughts (Griffiths and Efthekari 2008).

Gao et al. (2016) investigated indoor climate, window opening behavior, and pupil responses in classrooms with different types of ventilation system. Month-long measurements were made in a classroom with balanced central mechanical ventilation and in a classroom where windows were automatically opened and an exhaust fan ensured sufficient air intake. In addition, the study comprised two classrooms where the windows could be opened either manually or automatically (one-sided natural ventilation). The latter two classrooms were adapted from the same classrooms where windows were opened automatically and where the exhaust fan was installed. It was done by inactivating the fan or both the fan and the procedure for automatic opening of windows. Based on CO_2 measurements, Gao et al. (2016) found that the classroom with mechanical ventilation had the highest estimated average air-change rate and that windows were frequently opened in the nonheating season, but very seldom in the heating season.

Wargocki and Da Silva (2015) studied changes in window opening behavior when they provided visual feedback on the CO_2 concentration to pupils and teachers. The studies were performed during both the heating and nonheating seasons, for a week at a time. The pupils and teachers were instructed to open windows when CO_2 concentrations were above 1000 ppm, for example, when the feedback lamps were yellow or red. They observed that in periods when the visual feedback device was in operation, more windows were opened, resulting in reduced CO_2 concentration, but at the expense of increased energy use. During the heating season, Toftum et al. (2016) used the same visual feedback device during a week-long period, but gave different instructions to different classes in the same school. In one class, pupils were instructed to open windows when the CO_2 concentration was high. The other class was simply recommended to open the windows under these conditions. In two other classes without such visual feedback, pupils in one class were told that they must open the windows for 5 minutes during every lesson and in another class that they must open all the windows before leaving the classroom during the break. The effectiveness of each intervention was compared by measuring CO_2 concentrations prior to and after the interventions. In both classes with the visual feedback device, the occupied time during which the CO_2 concentration was above 1000 ppm was reduced by 40% to 60%, but the time when the classroom temperature was below 20°C seemed also to increase. The interventions without visual feedback had only negligible effects on the CO_2 concentration. However, recent measurements performed by pupils in 785 Danish classrooms showed that leaving the classroom and airing out during breaks reduced the percentage of classrooms with a CO_2 concentration higher than 1000 ppm from 60% to 39% compared to a condition when no windows were ever open (Clausen et al. 2014).

The current study was carried out within the framework of the ASHRAE RP-1624 project on "Effective Energy-efficient Classroom Ventilation for Temperate Zones." The overall objective of the study was to evaluate the performance of different methods of classroom ventilation in terms of the thermal and air quality in the classrooms, the window opening behavior of children and teachers, pupil's perceptions of the classroom environment, their reported health symptoms, their performance of school work, and energy use. The objective of the work presented in the current article was to measure CO_2 concentration, temperature and energy use, and to record window and door opening behavior during the heating season in classrooms retrofitted with different ventilation solutions.

Methods

School and classrooms

The school where the measurements were performed was located in a rural area north of Copenhagen, Denmark. There were 543 pupils in 25 classes with 2 to 3 classes at each grade level. Prior to installation of the ventilation retrofits, pupils and teachers had to open windows and doors manually

Fig. 1. Floor plan of school building with location of the classrooms evaluated (left) and picture of classroom from the outside (right).

if the classrooms were to be ventilated at all. This was not sufficient to ensure an acceptable classroom air quality. The municipality together with the school management therefore decided to retrofit selected classrooms with ventilation systems to make it possible to compare different retrofit solutions and select the one that was the best fit for the school. Different ventilation retrofits could, therefore, be compared in the same school building, instead of between schools.

The classrooms in which the retrofits were installed were located in a one-story building that had been commissioned in 1980: four different retrofits were installed in four classrooms and a fifth classroom served as a reference. The classrooms were occupied by 11- to 12-year-old pupils in 4th and 5th grade. Figure 1 shows the layout of the building and the location of the classrooms.

Each classroom had an area of 56 m^2 and a volume of 160 m^3. With a nominal number of 25 occupants (24 pupils plus 1 teacher), the minimum outdoor air supply rate as required by the Danish building code is about 520 m^3/h (145 l/s; Energistyrelsen 2014). In addition, the Danish building code requires that the classroom CO_2 concentration should not exceed 0.1% during extended occupancy periods. The nominal number of pupils in each class was between 23 and 26. The actual number of pupils present in the classrooms during the study period was typically between 22 and 25 pupils.

The classrooms had brick walls, acoustic ceilings, and linoleum floors. Figure 2 shows the interior, which was nearly identical in all the classrooms. The classrooms had overhead windows, windows in the façade with a view to the outdoor area, and two doors, one to a common area/hallway and one to the outdoor yard (Figure 3). Both the façade and overhead windows could be opened manually prior to installation of the retrofits. The location of the windows on two opposite facades enabled cross-ventilation in the classrooms. The windows in the façade of the classrooms where the retrofits were installed were replaced with new ones prior to installation of the retrofits. These were the classroom in which a mechanical supply and exhaust ventilation unit and the two in which automatic window opening was installed. In the other two classrooms the original, manually openable windows were retained.

All five classrooms were heated by water-filled radiators mounted below the façade windows and water-filled convectors below the overhead windows. Both radiators and convectors had manually adjustable thermostats.

The school was located in a temperate climate zone with mild winters and cool summers and the prevailing wind direction was west. Table 1 provides a summary of the actual weather conditions that were recorded during the measurement period.

Retrofit solutions

The four retrofit solutions for improving classroom ventilation were:

- A mechanical ventilation unit, with balanced supply and exhaust airflow that was controlled by the CO_2 concentration, was suspended from the ceiling of Classroom S3.

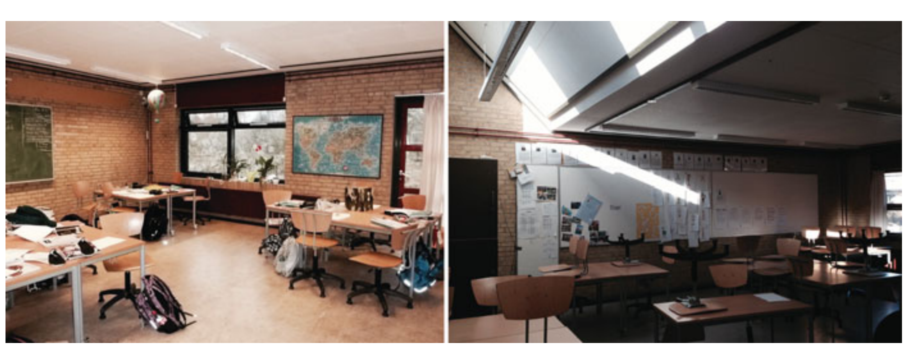

Fig. 2. Interior of a typical classroom.

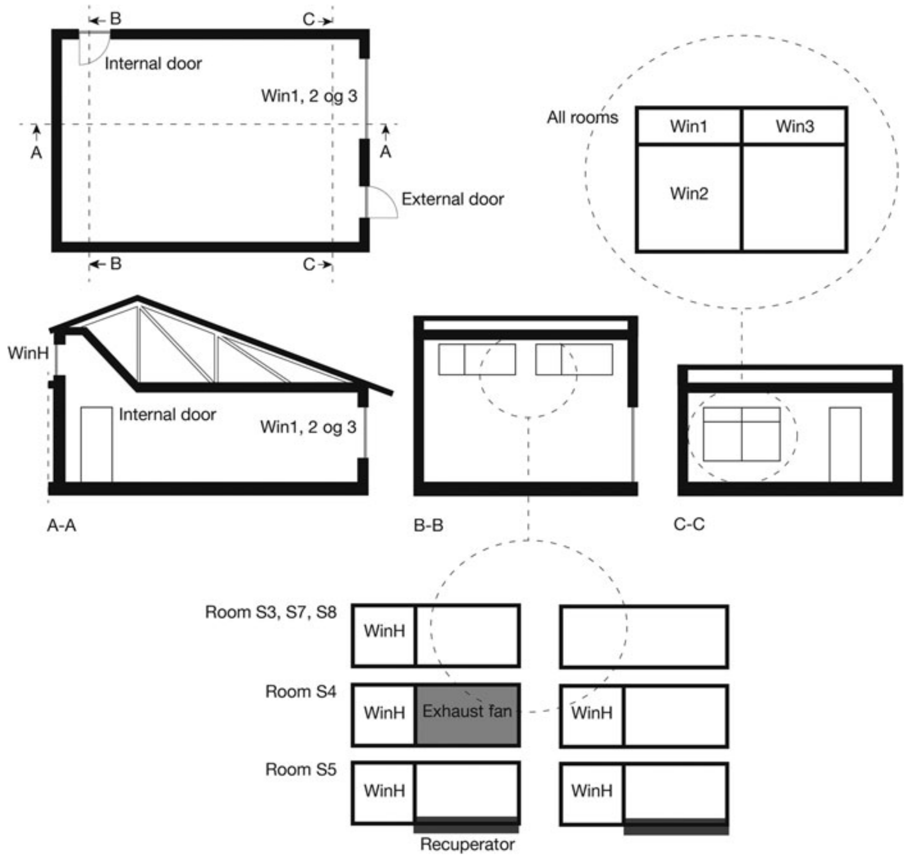

Fig. 3. Cross-section, floor plan, elevations of classroom, and location of openable windows (windows which could not be opened are not named).

- A system for natural ventilation by automatic window opening and an exhaust fan, both controlled by the CO_2 concentration, were installed in Classroom S4.
- A second system for natural ventilation by automatic window opening and five alternating counter-flow heat recovery units in slots in the outside wall, all six systems being controlled by the CO_2 concentration, were installed in Classroom S5.
- A visual CO_2 feedback display indicating when the CO_2 concentration was high and that windows, therefore, should be opened, was installed on the classroom wall in Classroom S8.

A mechanical ventilation unit was installed in Classroom S3. The unit was equipped with a filter (class EU7), a heat recovery unit, an electrical pre-heater, and a water-to-air heating coil. It had a maximum airflow rate of 725 m^3/h (201 l/s). The noise level at the maximum airflow was 35 dB(A) as specified by the manufacturer. The minimum airflow rate was 200 m^3/h (56 l/s). The low airflow rate was provided when the classroom CO_2 concentration was below 600 ppm; the airflow rate reached maximum at a concentration above 800 ppm. Between 600 and 800 ppm, the supply airflow rate increased linearly from the minimum to the maximum. The supply air temperature was adjusted by a thermostat to keep the room air temperature at 23 °C. The windows in this classroom could still be opened manually, independently of the operation of the mechanical ventilation system.

Table 1. Weather conditions aggregated for the entire measurement period from the January 7th to February 2 nd 2015 (including unoccupied periods).

	Min	Max	Median	Mean	SD
Air temperature, °C	– 2.4	10.3	2.5	2.9	2.2
Relative humidity, %	80.0	100.0	100.0	97.0	4.4
Wind speed, m/s	0.0	33.8	6.4	7.6	6.5

The actuators for the automatic window opening systems installed in Classrooms S4 and S5 operated the façade windows Win1, Win3, and the overhead window WinH (Figure 3). In both classrooms, the indoor CO_2 concentration, indoor air temperature, outdoor weather conditions and time of day were used as input to the window opening control system. A timer control was used to open the windows at the start of each clock hour of the school day if the CO_2 concentration was above 800 ppm. Unfavorable weather conditions with precipitation or strong winds caused the window opening degree to be reduced. The windows were controlled in so-called “pulse” and “trickle” modes; during the heating season, the “pulse” control mode typically dominated. When the CO_2 concentration increased rapidly to a level above 800 ppm, the “pulse” control mode opened the windows to the maximum opening degree for 3 minutes. In this mode and during the heating season (mid-October to mid-April), the maximum opening degree was 50% of the maximum achievable opening of the windows. During the nonheating season (mid-April to mid-September) it was 80%. The “trickle” control mode opened the windows gradually to the season-dependent maximum opening degree, when the CO_2 concentration increased from 750 to 1000 ppm. The control algorithm was over-ruled and windows were not opened when the indoor air temperature was below 19°C. The occupants had the possibility to manually over-ride the system by pushing a wall-mounted button, which opened the windows fully. When this happened, the system reverted to the original control setting 15 minutes after the button had been pushed. One of the lower windows could still be opened manually by pupils and teachers.

The automatic window control in Classroom S4 was accompanied by an exhaust fan. The fan was mounted in the overhead window opening to support cross-ventilation. The fan’s nominal airflow rate was 749 m^3/h (208 l/s) at a noise level of 40 dB(A) 10 meters from the fan as specified by the manufacturer. Operation of the exhaust fan started at a CO_2 concentration of 700 ppm and the maximum speed was reached at 1000 ppm. No heat was recovered from the exhaust flow. Supply air entered this classroom either through open windows or from the adjacent hall in cases when the fan was running and the windows were closed. This could be when the outdoor temperature was low and with strong winds. There was no indication that this situation occurred during the measurement period.

The automatic window control in Classroom S5 was accompanied by heat recovery units, each of which consisted of a heat absorbing material and a row of small fans. These units worked in pairs with opposite flow directions that reversed every minute. With exhaust airflow heat was absorbed and with supply airflow the absorbed heat preheated the cold supply air. The heat recovery units were installed in special slots in the outdoor wall; each section/unit contained five to seven small fans. Altogether, five units were installed and they could deliver outdoor air at a maximum rate of 468 m^3/h (130 l/s) at a low pressure loss, resulting in a SFP of 300 J/m^3. At the maximum airflow rate, the nominal noise level of one unit was approximately 35 dB(A) as specified by the manufacturer. Because of the operation principle any pollution trapped in the unit was reintroduced to the classroom. The thermal efficiency of the heat recovery was about 85%. The units were run at minimum speed when the CO_2 concentration in the classroom was below 650 ppm and their speed of operation was progressively increased to reach maximum airflow above a concentration of 750 ppm.

In Classroom S8, the display providing visual feedback on the CO_2 concentration was mounted on the wall. It had a scale consisting of LEDs showing the CO_2 concentration from 250 to 5000 ppm. The pupils and teachers were instructed to open the windows when the lights were yellow, for example, when the CO_2 concentration was above 1000 ppm. When the lights turned red, for example, when the CO_2 concentration exceeded 1600 ppm, they were instructed to open all windows and doors for 5 minutes to achieve cross-ventilation; during this time they were asked to leave the classroom. The pupils and teachers received instructions on how to respond to the feedback in October, for example, a few months prior to the present measurements.

The ventilation in the reference classroom was either single-sided, when either the façade or overhead windows were open, or two-sided (cross ventilation) when windows in both sides were open simultaneously. The overhead window could be opened by using a crank handle. Classrooms S7 and S8 had the same window configuration (Figure 3). As the Danish building code states that the classroom CO_2 concentration should not exceed 0.1% during extended periods, this value was used when comparing the performance of the different systems (Energistyrelsen 2014).

The retrofitted systems were in operation in January and February 2014 after being installed during the Christmas break of 2013/2014. Measurements described in the current article were made from January 7th to February 2 nd, 2015 during normal teaching activity after the retrofitted systems had been in operation for a full year (except during three separate weeks during which other experiments were carried out in October through November 2014). The visual feedback device had been in operation for approximately 4 months.

Measurements

One measurement station consisting of a Vaisala CO_2 transmitter model GMW22 (CO_2 range: 0–5000 ppm ± 100 ppm + 2% of reading) connected to an Onset HOBO data logger model U12-012 (signal range: ±2mV ±2.5% of reading) that also monitored temperature (range: –20 to 70 °C, ±0.35 °C in the range 0 to 50 °C) and relative humidity (RH; ±2.5% from 10% to 90% RH) was installed in each classroom. Measurements were recorded in 5-minute intervals during the 4 weeks from January 7th to February 2 nd, 2015. The measurement station was located away from the windows at a height of approximately 1.5 m above the floor next to the whiteboard. During another period (not reported in the current article) when an intervention study was carried out, but also in the heating season, two measurement stations were installed in each room; one next to the whiteboard and one at the back of the room. Convective currents caused by pupil movement and the temperature differences between their surface and the surrounding air resulted in well-mixed air, as indicated by nearly identical CO_2 concentrations measured at the two locations.

Window and door opening events were recorded with Onset HOBO State U9 Data Loggers with binary output. The state loggers recorded the events (window/door open/closed) and the time of the event. They were located on all the operable windows and the door frames in the classrooms.

In Classrooms S3, S4, and S5, the electricity used by the systems was logged. Energy meters were installed on the radiators, convectors, and the water-to-air heating coil in the mechanical system in Classroom S3. The window orientation in these rooms was the same (SSE), but the area of the external walls differed. One element of the overall study that was not reported in the current article was to simulate the energy

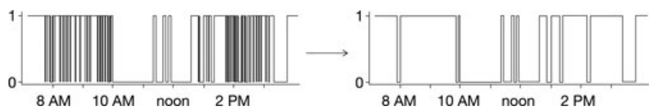

Fig. 4. Example of processing of event-based data for opening/closing of a door (1 = closed, 0 = open).

use of the classrooms in different climate zones. This was done based on the geometry of the school building and its material properties. From the simulation program, the authors adopted UA (heat transfer coefficient multiplied by area) factors for each classroom and used them to correct the heating energy use. U is the façade heat transmission coefficient and A the area. The reference classroom (S7) and the visual feedback device tested in Classroom S8 were included in the study by the authors after the municipality had completed installation of the retrofit solutions in the other three classrooms. Energy meters had, therefore, not been installed in these two classrooms.

Data processing

The measured CO_2 concentration, air temperature, and the opening state of windows and doors were merged in a common data set; all data were presented in 5-minute intervals. Data were aggregated for the occupied time defined as the lessons that took place in the classrooms. The breaks for recess and lunch were not included in the occupied time used when aggregating CO_2 concentrations and temperatures, as pupils typically spent these outside the classroom. However, break time was included in the analysis of the opening state of doors and windows, since these periods also affected the environment conditions in the classrooms during lessons.

Due to the event-based functionality of the instrumentation used to record window and door opening, the loggers in some cases indicated opening or closing of doors and windows in 1-second intervals and in other cases in e.g. 1-hour intervals. The periods with high frequency recordings were caused by windows or doors that were slightly ajar and could be moved by variations in the air pressure. The loggers, therefore, recorded many opening/closing events as the unit registered that the signal changed state. These periods were assumed to represent closed windows/doors. Figure 4 shows the results before and after adjustment of the events registered by the loggers. The analysis of window and door opening included not only the time classrooms were occupied, but the whole period from start to end of the measurements.

Data analysis

The effect of retrofits on classroom CO_2 concentration and temperature was compared by analysis of variance (ANOVA). In separate analyses, the ANOVA models examined the effect on the CO_2 concentration or temperature of the type of ventilation in the classroom adjusted for the measurement week, weekday, and the lesson within a day. Also, the models included all two-factor interactions between the main variables to adjust for the variability caused, for example, by the interaction between weekday and lesson. The analysis of the CO_2 concentration was made with log-transformed CO_2 concentrations due to the skewness of their distributions. Duncan's Multiple Range Test was used to allow for multiple comparisons. The residuals of both models were normally distributed.

The binary opening state of a window or door was compared between classrooms by logistic regression analysis. For each window and door in a classroom, the processed recordings of its opening state were aligned with concurrent recordings of CO_2 and temperature made every 5 minutes of the occupied time. The binary opening state was then used as the response variable in the analysis. Classroom, CO_2 concentration and temperature were used as explanatory variables. The logistic regression analysis compared only classroom S3 with the other classrooms and therefore Wald's test was used for pairwise comparison of all other combinations of classrooms.

Student's unpaired t-test was used to compare CO_2 concentrations measured in Classroom S3 between two periods when winH was left open and when it was closed (second versus first half of the measurement period).

All differences were considered significant at $p < 5\%$. The statistical analyses were carried out in R (University of Auckland, New Zealand) and Stata IC version 12.0 (Statacorp, TX, USA).

Results

Classroom CO_2 concentration and temperature

Figure 5 shows box-plots of the CO_2 concentrations and air temperatures measured in each classroom during the occupied school hours, excluding the breaks when pupils spent most of their time outside the classroom. In the classroom with the mechanical ventilation system (S3) and the classroom with automatic window control and an exhaust fan (S4), the CO_2 concentration was found to be significantly lower than in the other three classrooms ($p < 0.01$, ANOVA); the median CO_2 concentration in these classrooms was below 1000 ppm and the CO_2 concentration varied less, as indicated by a smaller inter-quartile range, than in the other three classrooms. No statistically significant differences were observed between the CO_2 concentrations measured in the other three classrooms S5, S8, and S7. All two-factor interactions included in the ANOVA model were significant at $p < 0.01$, indicating that the CO_2 concentration varied both between lessons within a day and between days within a week. The mean CO_2 concentration measured between 7:30 and 7:40 in all classrooms prior to arrival of pupils and teachers was 410 ppm (range 375 to 602 ppm).

The temperature was significantly higher in the classroom with visual feedback (S8) than in all the other classrooms ($p < 0.01$, ANOVA; Figure 5), presumably because the radiator thermostats were set higher. In this classroom, the median temperature was also higher than the recommended maximum heating season temperature of 24°C (ASHRAE 55–2013; ISO 15251-2007). The temperature in the classroom with the mechanical ventilation system (S3) was significantly higher than in the classrooms with automatic window

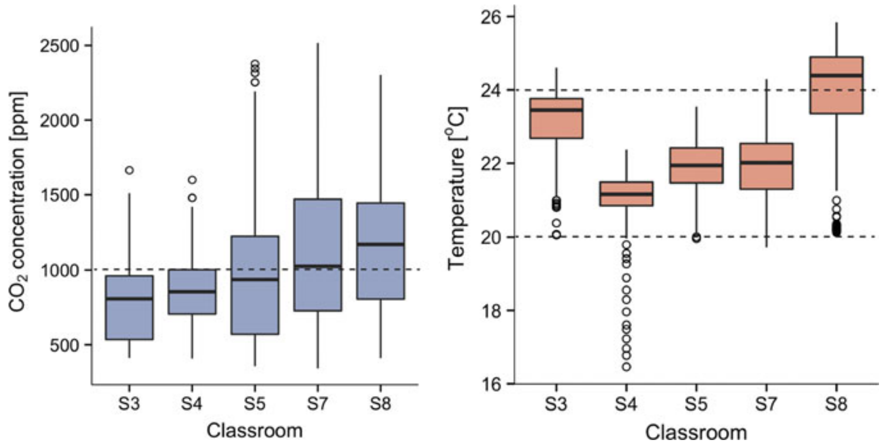

Fig. 5. Box-plots of the classroom CO_2 concentration (left) and indoor air temperature (right) in each classroom during the occupied period.

control (S4 and S5) and the reference classroom (S7; $p <$ 0.01, ANOVA). The temperature did not differ significantly between Classrooms S4, S5, and S7 and it was generally within the recommended thermal comfort range of 20°C to 24°C (ASHRAE 55–2013; ISO 15251-2007), although events with lower temperature were sometimes recorded in Classroom S4.

As an average over each of the 5 school days in the 3rd measurement week, Figure 6 shows profiles of the CO_2 concentration and temperature in each classroom together with the external temperature. The variability during the school day of the CO_2 concentration was smaller in S3, S4, and S5 than in the classrooms without dedicated ventilation systems. Also, the peak concentration was lower in these rooms, although in S4 and S5 the ventilation flow rate could not entirely sustain a CO_2 concentration below 1000 ppm. Temperatures varied between rooms, but the variation within classroom was rather modest during the school day.

Occupant interaction with windows and doors in the classrooms

For each day and time of day during the measurement period, Figure 7 shows the number of windows opened simultaneously; Figure 8 provides similar information on the opening state of the two doors in each classroom. Many frequent opening events of short duration were observed in classrooms S4 and S5 where the windows were opened automatically, compared with the other classrooms. In S4 and S5, the teachers and pupils opened windows manually for only 5% of the time. In the reference classroom (S7) and the classroom in which visual feedback on CO_2 was provided (S8), the windows were rarely opened. In classroom S3 with mechanical ventilation, one window (winH) was left open during the entire second half of the measurement period. This seems not to have affected the temperature, which was generally higher in this classroom than in the other rooms. However, the CO_2 concentration was significantly higher during the first period with a closed winH than during the second period with an open winH (median 899 ppm versus 564 ppm; $p < 0.05$, *t*-test).

The external door in the classrooms with dedicated ventilation systems (S3, S4, and S5) was generally opened less frequently than in S7 and S8 ($p < 0.05$, logistic regression). Events with two open doors were more prevalent in the reference classroom (S7) and in the classroom with the visual feedback display (S8), as could be expected (Figure 8). The door to the hall was left open or ajar in S4 for an extended period and for a few days in S3 and S5.

For each classroom, Figure 9 shows the percentage of the occupied time when each of the doors and windows was open, aggregated for the whole measurement period. The

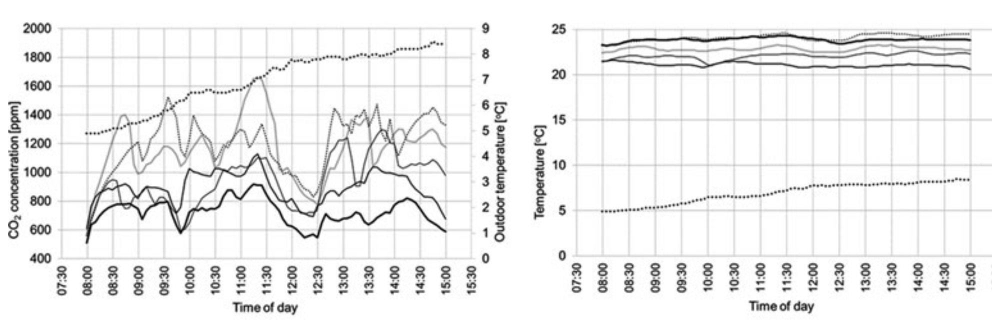

Fig. 6. CO_2 concentration (left) and temperature (right) in each classroom during a school day (average over each of the five school days in the third measurement week). The figures also show the average external temperature.

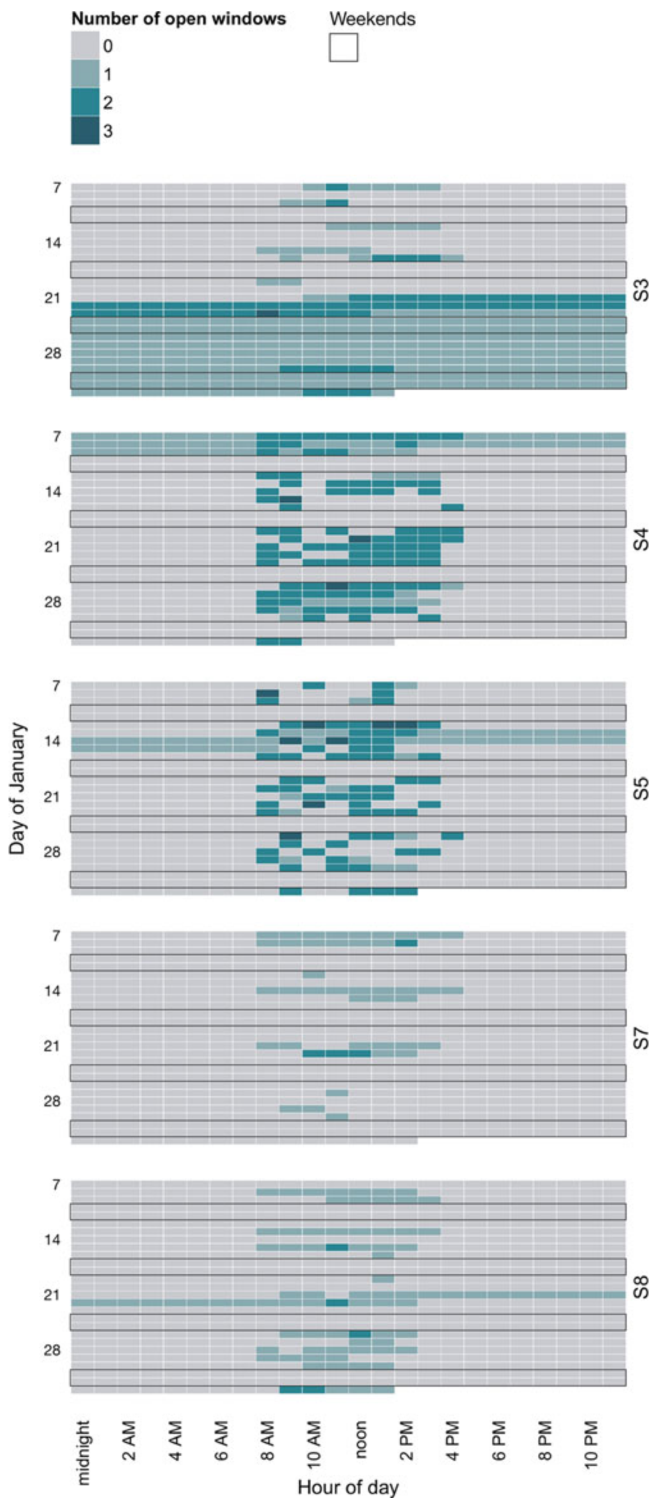

Fig. 7. Number of open windows as a function of day and time of day during the measurement period.

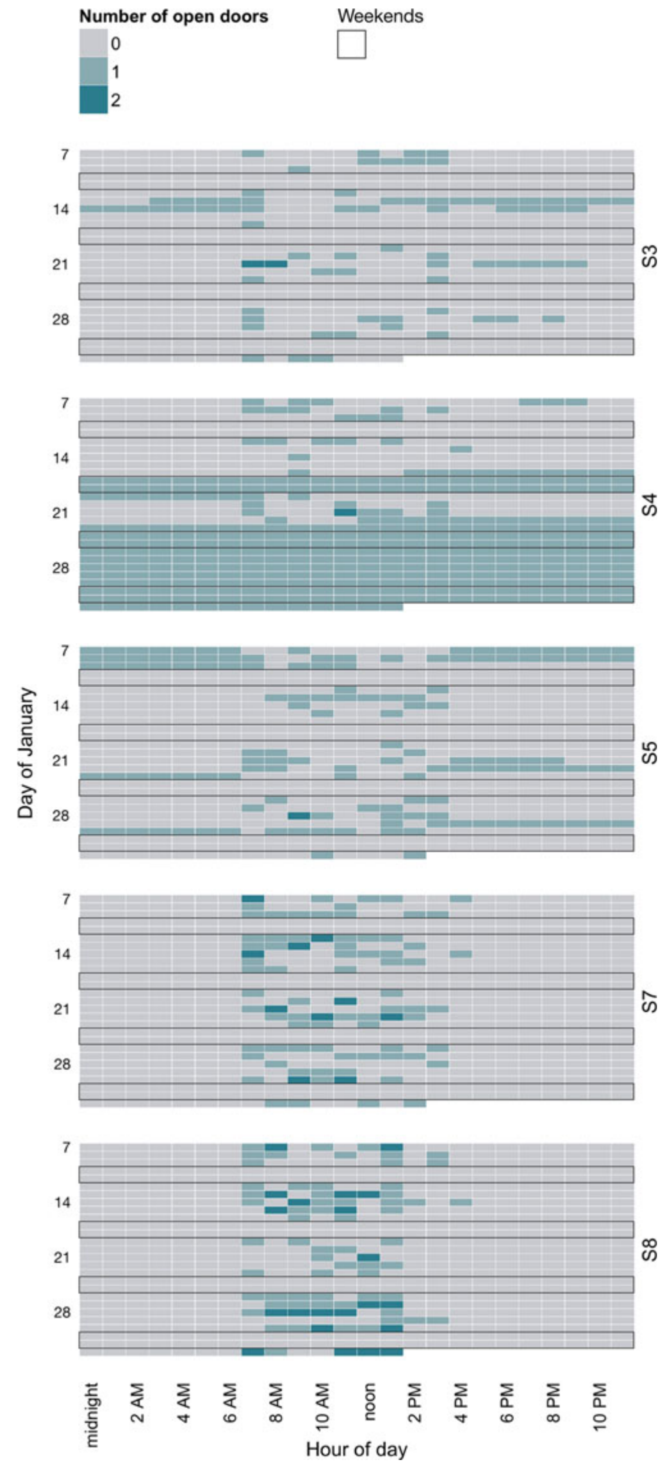

Fig. 8. Number of open doors as a function of day and time of day during the measurement period.

door to the yard was open for only 1% to 2% of the occupied period in the classrooms with dedicated ventilation systems. In contrast, this door was open for 31% and 33% of the occupied period in the reference classroom (S7) and the classroom with visual feedback (S8), respectively. The entrance door in the classroom with automatic window opening and an exhaust fan (S4) was open for 47% of the occupied period (Figure 8), mostly during the second half of the measurement period (Figure 7). This could be due to a particular teacher, who did not mind that there was a door open during lessons.

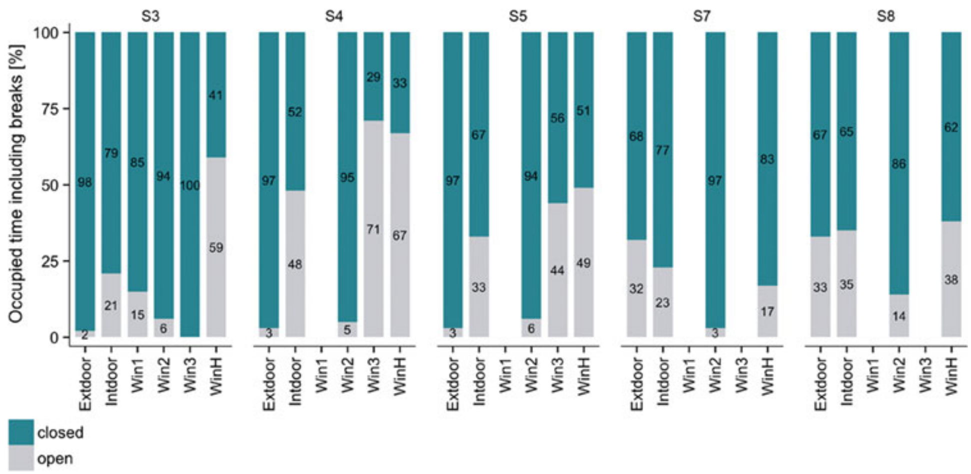

Fig. 9. Percentage of the occupied period including breaks in each classroom with open or closed doors and windows. In S7 and S8 Win 1 and Win 3 could not be opened.

Figure 9 shows that the façade windows were open for less than 15% of the occupied period including breaks in the classrooms without automatic control of window opening (S3, S7, and S8). In comparison, the windows that were automatically controlled (Win3 and WinH) in classrooms S4 and S5 were open for 44% to 71% of the occupied time. Particularly low temperatures were measured in S4, and this corresponded well with the lower CO_2 concentrations measured in this room, indicating an increased supply of cold outdoor air due to the frequent opening of the windows in combination with the exhaust fan.

WinH and Win2 in the classroom with visual feedback (S8) were open more frequently than in the reference classroom (S7; $p < 0.05$, logistic regression), suggesting that the visual CO_2 feedback had some impact on the pupils' and teachers' window opening behavior (Figure 9). However, the CO_2 concentration measured in S8 did not differ significantly from what was measured in the reference classroom.

Energy use

Table 2 shows the energy used by the systems in each of the retrofitted classrooms from January 7 to February 2. The heating energy use was compensated for the difference in UA between the classrooms according to the correction factors shown in Table 2. In the two classrooms with automatic window control and an exhaust fan or the heat recovery units, the use of heating energy included the radiator under the façade windows and the convector below the overhead windows. In the classroom with the mechanical ventilation system the energy used by the water-based heating coil was also included. The electricity use included the energy used by the fans in the mechanical ventilation system, the exhaust fan and the fans in the heat recovery units as well as by the actuators that opened the windows. Auxiliary electricity use (computer for central management of all systems, wiring closet, etc.) is not included in the values presented in Table 2.

Discussion

This study was undertaken to evaluate system performance and occupant interaction with windows and doors in classrooms in which retrofitted ventilation solutions had been installed and were being operated as they would be in any given school subject to a similar retrofit. The current measurements and observations, therefore, reflect the variation in indoor environment, occupant behavior, and energy use that can be expected in schools with similar retrofits, when they are located in temperate climates, during the heating season. The present study built partly on the methodology used previously by Gao et al. (2016) and Wargocki and Da Silva (2015). However, one important distinction between these and the present study was that in the present experiments the examined solutions had been in use for 1 year, except the visual feedback device, which had been used through 4 months. The different retrofits were thus, not installed temporarily

Table 2. Use of heating and electrical energy in the sub-metered classrooms (S3, S4, S5).

	Mechanical ventilation system (S3)	Hybrid solution with exhaust fan (S4)	Hybrid solution with heat recovery (S5)
Electricity use, kWh	10.7	10.2	8.9
Measured heating use, kWh	646	365	259
Correction factor	1*)	1.02	1.11
Corrected heating use, kWh	646**)	372	287

*)Measured heating energy use was multiplied with the correction factor to compensate for differences in external wall area.
**)A malfunctioning valve may have affected the heating provided by the mechanical ventilation system.

for the purpose of the experiments. Consequently, the pupils and teachers were used to them before the measurement campaign was started. Another distinction was that the use of visual feedback was monitored for 1 month and not for 1 week. Finally, the measurements included also monitoring of the energy used for both heating and ventilation.

Lower CO_2 concentrations and lower variation in the CO_2 concentration were observed in the classrooms with dedicated ventilation systems as compared with the classrooms with the other systems. However, the CO_2 concentration was significantly lower only in the classroom with the mechanical ventilation system (S3) and with the automatic window opening and an exhaust fan (S4). The maximum supply airflow achieved by the heat recovery units in S5 was only 60% to 65% of the maximum airflow rate of the mechanical ventilation system in S3 and of the exhaust fan in S4. The supplementary ventilation provided by the heat recovery units was insufficient to significantly reduce the CO_2 concentrations.

During the heating season, the motivation of pupils and teachers to manually open windows is generally quite low. This was shown by Gao et al. (2014) and Wargocki and Da Silva (2014), and also observed in the current study in the reference classroom (S7), where the windows were rarely opened. There could be several reasons why pupils open the windows less frequently when it is cold outside, but the most obvious is that a low outdoor temperature causes cold draughts when windows are open. During the present measurements the average outdoor temperature was around 3°C and the maximum temperature for the whole period was 10°C. Temperatures in this range may be sufficiently low to discourage the teachers and pupils from opening the windows.

In the classroom with a visual feedback display (S8) windows were opened for longer than in the reference classroom (S7), but this did not reduce the CO_2 concentration significantly. This finding differs from what was found in other studies in which a similar visual feedback display did significantly reduce the measured CO_2 concentration in classrooms (Toftum et al. 2016; Wargocki and Da Silva 2015). A possible explanation for this difference could be that the pupils simply forgot to pay any attention to the feedback display because it had been present in the classroom for several months already. This may indicate that users of such devices should be regularly reminded to act upon the feedback provided. As an alternative to the one used in this study, a visual display unit with a larger or animated display that attracts more attention or one that is supplemented by an auditory signal may be more efficient in promoting manual opening of windows when needed.

Periods with simultaneously open windows or doors were very limited in both classrooms, for example, cross-ventilation rarely occurred. Figures 7 and 8 show that opening events were typically clustered within the same time slots. The visual feedback display did not result in more time with an open door to the outdoors than in the reference classroom, but in both these rooms this door was open for longer than in the other three classrooms. This could also have been for other reasons than poor classroom air quality, for example, easier access to the outdoor playground. The air temperatures in the classroom with a visual feedback display were significantly higher than in the reference classroom, possibly due to a different thermostat setting.

The façade windows were open 71% of the occupied period in Classroom S4 (with automatic window opening and an exhaust fan). In Classroom S5 (with automatic window opening and heat recovery units), the façade windows were open for only 44% of the time. In S4 the CO_2 concentration was lower, which suggests that the duration of time with open windows was an important factor contributing to the reduction of the CO_2 concentration. However, as the classrooms used two different systems for forced ventilation it is difficult to attribute the lower CO_2 concentration solely to the time for which windows were open. Although the temperature did not differ significantly between S4 and S5, the median temperature was approximately 1°C lower in S4 than in S5, as the heat recovery units delivered air at a median temperature of about 19°C (estimated with a thermal efficiency of 0.85, a median indoor temperature of 22°C and median outdoor temperature of 2.5°C). Due to the heat recovery and the reduced time with windows open, the heating energy used in S5 was lower than in S4.

Neglecting the presumably forgotten open or slightly ajar WinH in S3 with the mechanical ventilation system, windows and doors to the outside in this classroom were open between 2% and 15% of the occupied time. In this room, the CO_2 concentration was the lowest. However, the average indoor air temperature was rather high, possibly due to a malfunctioning valve in the ventilation system, which, therefore, supplied air at a temperature that was too high. The valve defect was not discovered until after completion of the measurement period so the heating energy use in S3 may not reflect what can be expected with a correctly functioning system. Unfortunately, the defective valve in the mechanical ventilation system also invalidated meaningful comparison of energy use between classrooms S3, S4, and S5.

In the present study, the measured CO_2 concentration (together with the measured temperature and energy use) was used a performance metric for the different retrofit solutions. The CO_2 concentration is usually used as a proxy for ventilation, but in the current study the authors did not attempt to estimate ventilation rate. The estimation has several limitations and requires precise knowledge on the number of occupants, their CO_2 generation rate (metabolic rate) as well as knowledge on airflows between adjacent spaces. Rather than making these assumptions, it was assumed that lower CO_2 concentration may imply higher ventilation rate and better indoor air quality. It seems justified to make this assumption, as it has been made earlier in recognized studies (e.g., Daisey et al. 2003; Griffiths and Efthekari 2008; Twardella et al. 2012). The measured CO_2 concentrations were below the 8-hour maximum permissible occupational exposure level of 5000 ppm (OSHA 2017). Also, there is no conclusive evidence that CO_2 itself among adults should increase the risk of discomfort or health problems or the cognitive performance of simple tasks (Liu et al. 2017; Zhang et al. 2016, 2017), although demanding cognitive tasks have been shown to be affected (Allen et al. 2016; Satish et al. 2012). CO_2 at the concentrations measured in the current study should thus not be considered a toxic compound.

In summary, the present measurements during the heating season confirmed that manual opening of windows in schools located in moderate climate zones rarely takes place. Therefore, it is less reliable in improving the classroom air quality than retrofits with automatically controlled ventilation. The installed nominal capacity of the controlled systems should match code requirements for minimum airflow, even if additional ventilation can be achieved by automatic opening of windows.

Conclusions

- With a visual CO_2 feedback display in the classroom, windows were open for a greater proportion of the occupied time including breaks than in the reference classroom, in which windows were also opened manually, but this did not result in significantly lower CO_2 concentrations.
- In a classroom with automatic window opening and an exhaust fan, windows were open for 71% of the occupied period including breaks, which resulted in significantly lower CO_2 concentrations than in the classrooms with only manual opening of windows and doors.
- In a classroom with automatic window opening and heat recovery units, windows were open for 49% of the occupied period including breaks, but this did not result in significantly lower CO_2 concentrations than in the two classrooms with manual window opening.
- The lowest CO_2 concentrations were measured in the classroom with a mechanical ventilation system and the classroom with automatic window opening and an exhaust fan.
- The temperature did not differ significantly between the classroom without any retrofit and the classrooms with automatic window opening, and it was generally within the recommended thermal comfort range. In the classrooms with a visual CO_2 feedback display or with mechanical ventilation system temperatures were significantly higher than in the other rooms. The settings of the radiator thermostats and a malfunctioning valve in the mechanical ventilation system may have caused the system to supply air at a temperature that was too high.

Acknowledgments

Professor David P. Wyon is acknowledged for careful proofreading of the manuscript and for his many suggestions that considerably improved the manuscript. The authors sincerely appreciate the willingness of the pupils, teachers, and management at Ravnsholtskolen to participate in the present study.

Funding

The current study was funded by the American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE) as part of research project 1624-RP. The companies Windowmaster and Airmaster provided the retrofit solutions and the municipality of Allerod paid for their installation.

References

Allen, J.G., P. MacNaughton, U. Satish, S. Santanam, J. Vallarino, and J.D. Spengler. 2016. Associations of cognitive function scores with CO_2, ventilation, and volatile organic compound exposures in office workers: A controlled exposure study of green and conventional office environments. *Environmental Health Perspectives* 124(6):805.

ASHRAE. 2013. *Standard 55 Thermal Environmental Conditions for Human Occupancy*. Atlanta: ASHRAE.

Bakó-Biró, Z., D.J. Clements-Croome, N. Kochhar, H.B. Awbi, H., and M.J. Williams. 2012. Ventilation rates in schools and pupils' performance. *Building and Environment* 48:215–23.

Clausen, G., J. Toftum, and B. Andersen. 2014. Indeklima i klasselokaler—Resultater Masseeksperiment (Indoor environment in classrooms—Results), Danish Science Factory & Technical University of Denmark. http://masseeksperimentet.danishsciencefactory.dk/ (in Danish).

Daisey, J.M., W.J. Angell, and M.G. Apte. 2003. Indoor air quality, ventilation and health symptoms in schools: An analysis of existing information. *Indoor Air* 13(1):53–64.

Dutton, S., and L. Shao. 2010. Window opening behaviour in a naturally ventilated school. *SimBuild* 2010:260–8.

Energistyrelsen. 2014. Bygningsreglement 2010 (Danish Building Code 2010), BR10. http://bygningsreglementet.dk.

Fabi, V., R.V. Andersen, S.P. Corgnati, and B.W. Olesen. 2013. A methodology for modelling energy-related human behaviour: Application to window opening behaviour in residential buildings. *Building Simulation* 6(4):415–27.

Gaihre, S., S. Semple, J. Miller, S. Fielding, and S. Turner. 2014. Classroom carbon dioxide concentration, school attendance, and educational attainment. *Journal of School Health* 84(9):569–74.

Gao, J., P. Wargocki, and Y. Wang. 2014. Ventilation system type, classroom environmental quality and pupils' perceptions and symptoms. *Building and Environment* 75:46–57.

Griffiths, M., and M. Efthekari. 2008. Control of CO_2 in a naturally ventilated classroom. *Energy and Buildings* 40:556–60.

Gunnarsen, L., and P.O. Fanger. 1992. Adaption to indoor air pollution. *Environment International* 18(1):43–54.

Haverinen-Shaughnessy, U., D.J. Moschandreas, and R.J. Shaughnessy. 2011. Association between substandard classroom ventilation rates and students' academic achievement. *Indoor Air* 21(2):121–31.

Hellwig, R.T., F. Antretter, and A. Holm. 2009. Investigations on indoor environmental conditions and natural ventilation in school buildings. *Bauphysik* 31(2):89–98.

ISO Standard 15251. 2007. *Indoor Environmental Input Parameters for Design and Assessment of Energy Performance of Buildings Addressing Indoor Air Quality, Thermal Environment, Lighting, and Acoustics*. Geneva, Schwitzerland: International Organisation for Standardisation.

Liu, W., W. Zhong, and P. Wargocki. 2017. Performance, acute health symptoms and physiological responses during exposure to high air temperature and carbon dioxide concentration. *Building and Environment* 114:96–105.

Mendell, M.J., E.A. Eliseeva, M.M. Davies, M. Spears, A. Lobscheid, W.J. Fisk, and M.G. Apte. 2013. Association of classroom ventilation with reduced illness absence: A prospective study in California elementary schools. *Indoor Air* 23(6):515–28.

Rosbach, J., E. Krop, M. Vonk, J. van Ginkel, C. Meliefste, S. de Wind, U. Gehring, and B. Brunekreef. 2016. Classroom ventilation and indoor air quality—Results from the FRESH intervention study. *Indoor Air* 26:538–45.

Santamouris, M., A. Synnefa, M. Asssimakopoulos, I. Livada, K. Pavlou, M. Papaglastra, and V. Assimakopoulos. 2008. Experimental investigation of the airflow and indoor carbon dioxide concentration in classrooms with intermittent natural ventilation. *Energy and Buildings* 40(10):1833–43.

Satish, U., M.J. Mendell, K. Shekhar, T. Hotchi, D. Sullivan, S. Streufert, and W.J. Fisk. 2012. Is CO2 an indoor pollutant? Direct effects of low-to-moderate CO_2 concentrations on human decision-making performance. *Environmental Health Perspectives* 120(12):1671.

Shendell, D.G., R. Prill, W.J. Fisk, M.G. Apte, D. Blake, and D. Faulkner. 2004. Associations between classroom CO_2 concentrations and student attendance in Washington and Idaho. *Indoor Air* 14(5):333–41.

Stabile, L., M. Dell'Isola, A. Frattolillo, A. Massimo, and A. Russi. 2016. Effect of natural ventilation and manual airing on indoor air quality in naturally ventilated Italian classrooms. *Building and Environment* 98:180–9.

Toftum, J., B.U. Kjeldsen, P. Wargocki, H.R. Menå, E.M.N. Hansen, and G. Clausen. 2015. Association between classroom ventilation and learning in Danish schools. *Building and Environment* 92 (October 2015):494–503.

Toftum, J., M.M. Wohlgemuth, U.S. Christensen, G. Bekö, and G. Clausen. 2016. Managed airing behaviour and the effect on pupil perceptions and indoor climate in classrooms. *Indoor Air Proceedings 2016, Ghent, Belgium, July 3–8, 2016, paper no. 500*.

Twardella, D., W. Matzen, T. Lahrz, R. Burghardt, H. Spegel, L. Hendrowarsito, A. Frenzel, and H. Fromme. 2012. Effect of classroom air quality on students' concentration: Results of a cluster-randomized cross-over experimental study. *Indoor Air* 22(5): 378–87.

U.S. Department of Labor, Occupational Safety and Health Administration. 2017. Code of Federal Regulations, Title 29, Part 1910.1000-1910.1450. www.osha.gov.

Wargocki, P., and N.A.F. Da Silva. 2015. Use of visual CO_2 feedback as a retrofit solution for improving classroom air quality. *Indoor Air* 25(1):105–14.

Wargocki, P., J. Sundell, and W. Bischof. 2002. Ventilation and health in non-industrial indoor environments. *Indoor Air* 12(2):113–28.

Wargocki, P., and D. Wyon. 2013. Providing better thermal and air quality conditions in school classrooms would be cost-effective. *Building and Environment* 59:581–9.

Wyon, D.P., P. Wargocki, J. Toftum, and G. Clausen. 2010. Classroom ventilation must be improved for better health and learning. *The REHVA European HVAC Journal* 47(4):35–9.

Zhang, X., P. Wargocki, and Z. Lian. 2016. Human responses to carbon dioxide, a follow-up study at recommended exposure limits in non-industrial environments. *Building and Environment* 100: 162–71.

Zhang, X., P. Wargocki, Z. Lian, and C. Thyregod. 2017. Effects of exposure to carbon dioxide and bioeffluents on perceived air quality, self-assessed acute health symptoms, and cognitive performance. *Indoor Air* 27(1):47–64.